Optimal walking gait with double support, simple support and impact for a bipedal robot equipped of four-bar knees

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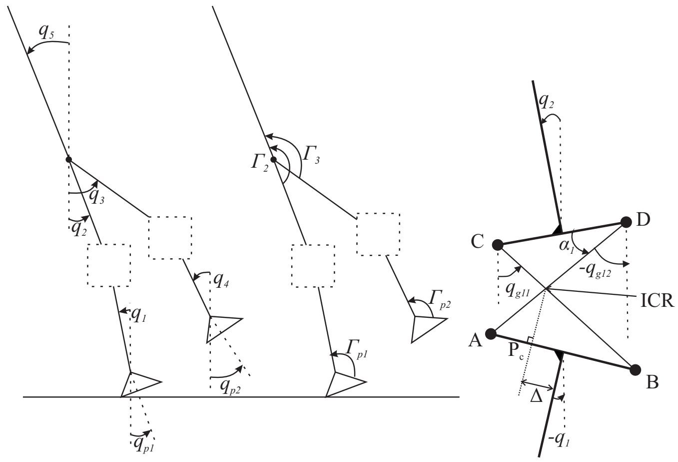
Abstract

The design of a knee joint is a key issue in robotics and biomechanics to improve the compatibility between prosthesis and human movements and to improve the bipedal robot performances. We propose a novel design for the knee joint of a planar bipedal robot, based on a four-bar linkage. This advantage of this structure is to produce a translation of the Instantaneous Center of Rotation (ICR) of the knee joint like in the human case. The schematic of this robot with a detailed view of the four-bar knee is given on figure 1.



(a) (b)

Figure 1: a) Schematic of a planar bipedal robot. Absolute angular variables and torques. b) Details of the four-bar linkage and position of the Instantaneous Center of Rotation (*ICR*)

In previous a work, we have proved a bipedal robot with four-bar knees has a less energy consumption than a bipedal robot equipped of revolute knee joints for walking gates composed of single support phases separated by impulsive impact, [1]. Our objective in this work is to extend this result for walking motion which included double support phase with a feet rotation. For that, we use a parametric optimization method to produce reference walking trajectories which minimize the energy consumption and respect different constraints to ensure a feasible movement. The computation of the energy consumption needed to define a dynamic model of the biped.
The general dynamic model in double support is given by :

$$\mathbf{A}(\mathbf{x})\ddot{\mathbf{x}}+\mathbf{h}(\mathbf{x},\dot{\mathbf{x}}) = \begin{bmatrix}\mathbf{D}_\Gamma & \mathbf{J}_1^t & \mathbf{J}_2^t\end{bmatrix}\begin{bmatrix}\boldsymbol{\Gamma}_{\boldsymbol{m}} \\ \mathbf{f_c}\end{bmatrix} + \mathbf{J}_{r_1}^t\mathbf{r}_1 + \mathbf{J}_{r_2}^t\mathbf{r_2} \tag{1}$$

here x is the vector of the generalized coordinates of the biped, $\boldsymbol{\Gamma}_{\boldsymbol{m}}$ is the vector of the torque, $\mathbf{r_1}$ and $\mathbf{r_2}$ represent the reaction forces of the ground on both feet. $\mathbf{J}_1$ and $\mathbf{J}_2$ are the Jacobian matrices used to take into account the closed loop constraints on the four-bar knees with force $\mathbf{f_c}$.
The studied trajectories are composed of double support phases and single support phases. During the double support phase, we denote a rotation of the forward foot around the heel and a rotation of the backward foot around the toe. The double support phase is ended by the flat contact of the forward foot on the ground. The single support phase is ended by the contact of the swing foot on the toe.
The impact model is obtained through the integration of the dynamic model 1 from $\dot{\mathbf{x}}^-$ (the instant just before the impact) to $\dot{\mathbf{x}}^+$ (the instant just after the impact).

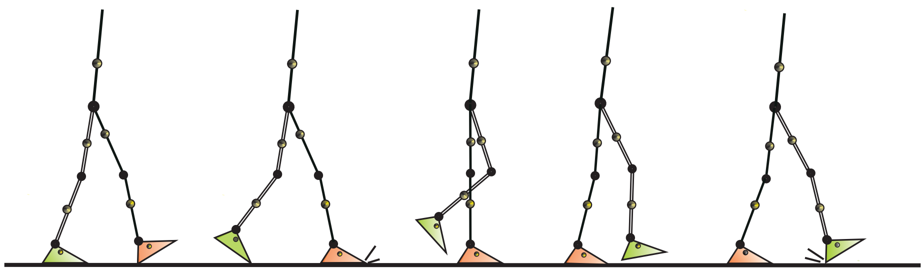


Figure 2: Presentation of the studied walking gait.

$$\mathbf{A}(\mathbf{x}(T))(\dot{\mathbf{x}}^{+}-\dot{\mathbf{x}}^{-})=\begin{bmatrix}\mathbf{J}_1^{\mathrm{t}} & \mathbf{J}_2^{\mathrm{t}}\end{bmatrix}\mathbf{i}_{fc}+\mathbf{J}_{r_1}^{\mathrm{t}}\mathbf{i}_1+\mathbf{J}_{r_2}^{\mathrm{t}}\mathbf{i}_2 \tag{2}$$

with the constraints on the closed loop of the knee just after the impact :

$$\begin{bmatrix}\mathbf{J}_1\\ \mathbf{J}_2\end{bmatrix}\dot{\mathbf{x}}^{+}=\mathbf{0} \tag{3}$$

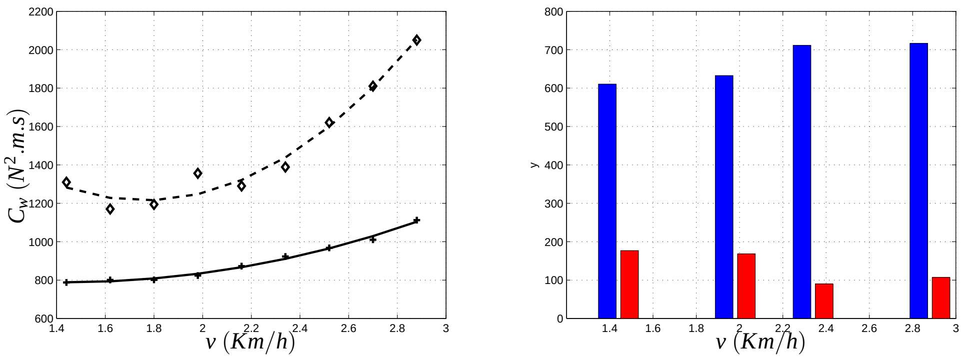
and the contact constraints on the first foot just after the impact :

$$\mathbf{J}_{r_1}\dot{\mathbf{x}}^{+}=\mathbf{0}. \tag{4}$$

In the case of a double support phase after an impact, the constraints on the second foot are :

$$\mathbf{J}_{r_2}\dot{\mathbf{x}}^{+}=\mathbf{0} \tag{5}$$

In our case the Jacobian matrix $\mathbf{J}_{r_2}$ represents the toe of the backward foot.
With an optimization process, we developped a set of optimal trajectories for different walking velocities for a biped equipped of four-bar knees and for a biped equipped of revolute knees. We can see, on figure 3.a, the evolution of the energy consumption according to the walking velocities for both solutions of knee joints. We observe an important reduction of the energy consumption by using of four-bar knees. In both cases of knee joints, the optimization process converges on a feasible motion with double support phase despite the inclusion of impact between each phase. Finally, the figure 3.b shows an important energy consumption during the double support phase for the biped equipped of four-bar knees. This phase plays the role of propulsion.



(a) (b)

Figure 3: a) : Total energy consumption(straight line : biped with four-bar knees, dashed line : biped with revolute knees). b) : energy consumption for the double support phase (blue line) and for the single support phase (red line) for both solutions of knee joints and for different walking velocities.

References

[1] HAMON, A., AND AOUSTIN, Y. Cross four-bar linkage for the knees of a planar bipedal robot. In *2010 IEEE-RAS International Conference on Humanoid Robots* (2010), pp. 379–384.